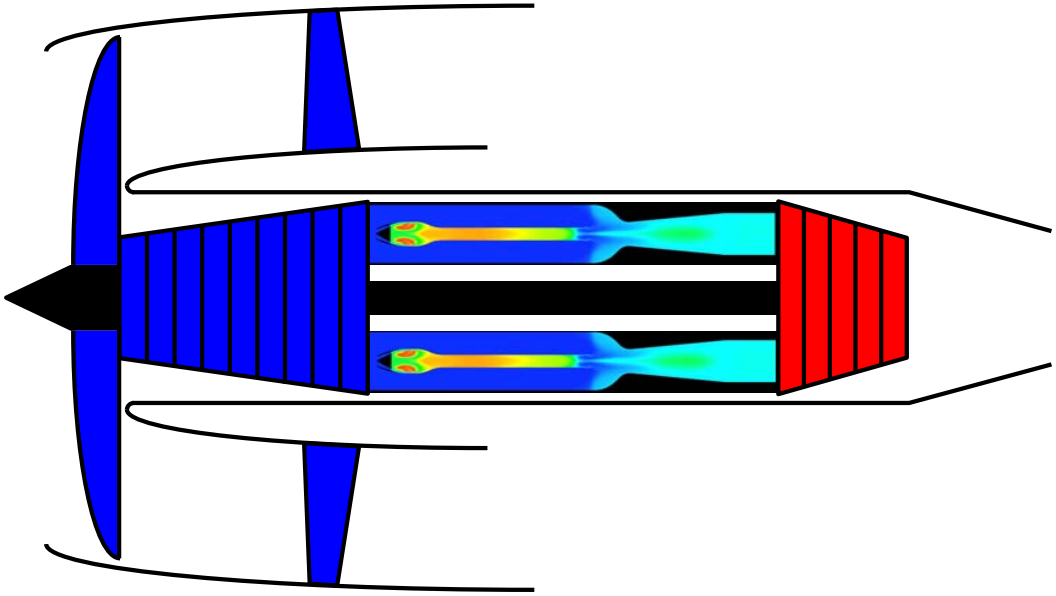

Resonant Pulse Combustors: A Reliable Route to Practical Pressure Gain Combustion

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- Kevin Dougherty - Experiments
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- Paul Litke - Experiments
- Andy Naples - Experiments
- Mark Wernet - PIV
- Trevor John - PIV

Outline

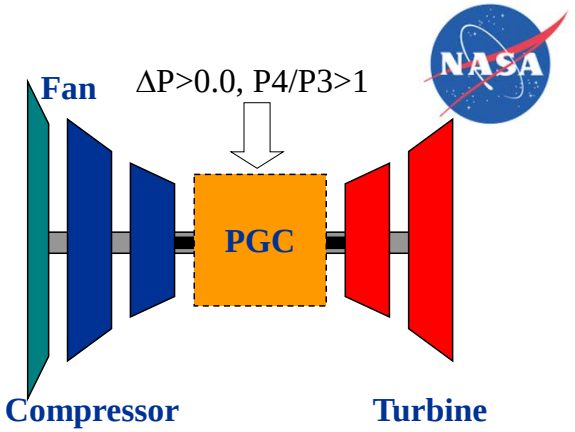
- Motivation
- Experimental Investigations
- Numerical Investigations
- Ongoing and Future Directions
- Concluding Remarks

Pressure Gain Combustion (PGC) Defined:

A fundamentally unsteady process whereby gas expansion by heat release is constrained, causing a rise in stagnation pressure and allowing work extraction by expansion to the initial pressure.

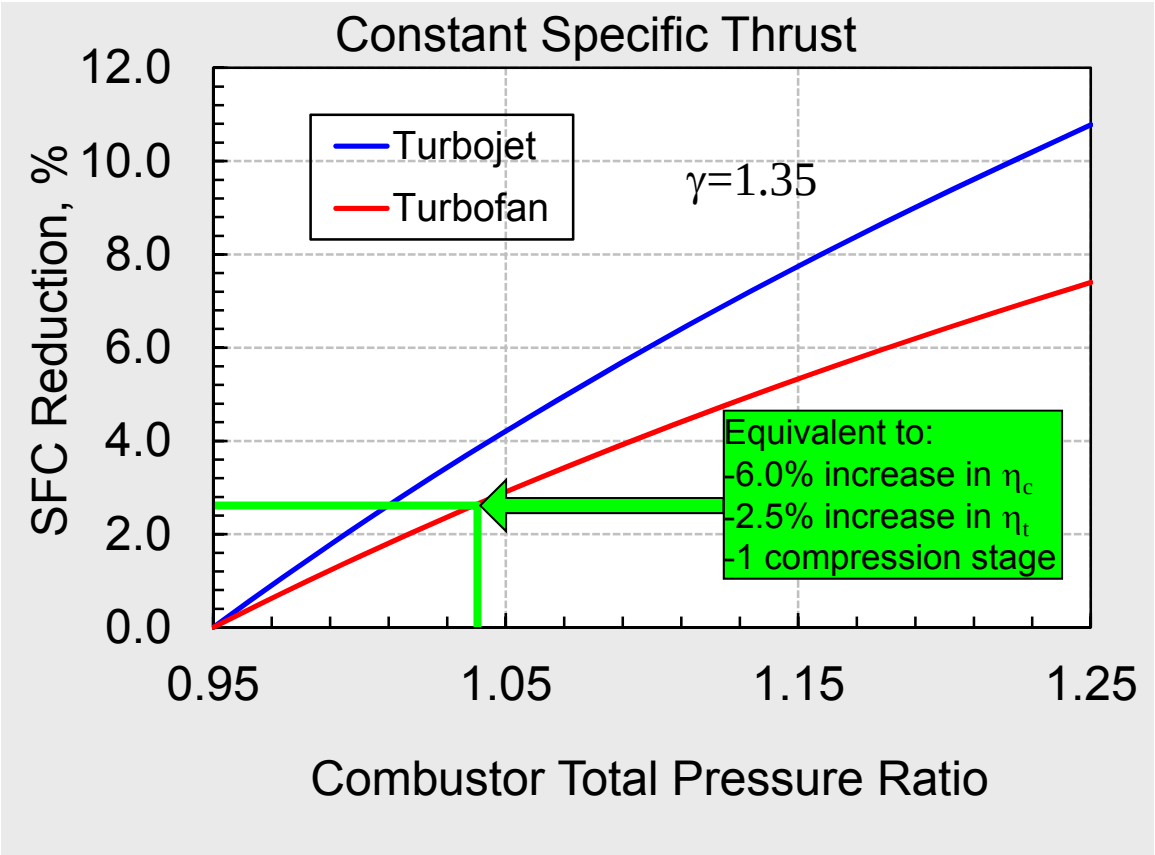
Context:
Our Focus Is Not the Promotion of Any One PGC Mode
It Is the Practical Utilization of Confinement

Motivation



Pressure Gain Combustion Theoretically:

+Increases thermodynamic cycle efficiency
+Reduces SFC / fuel burn (NASA Objective)
+Reduces greenhouse gas emissions (NASA Objective)
+Competes with conventional cycle improvements

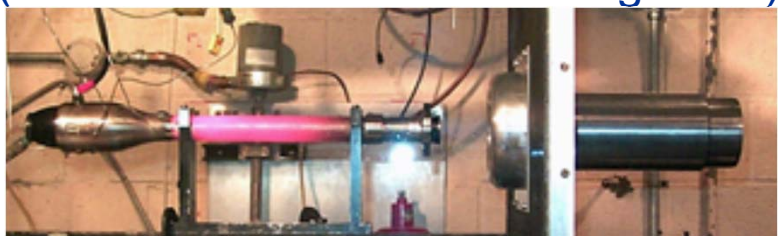


Engine Parameter	Turbofan	Turbojet
OPR	30.00	8.00
η_c	0.90	0.90
η_t	0.90	0.90
Mach Number	0.80	0.80
T_{amb} (R)	410	410
$T_{combustor\ exit}$ (R)	2968	2400
Burner Pressure Ratio	0.95	0.95
T_{sp} (lb_f-s/lb_m)	18.26	75.86
SFC (lb_m/hr/lb_f)	0.585	1.109

Low NOX Constraint on All Concepts

Motivation

Resonant **P**ulse **C**ombustor-RPC
(aka 'Confined' Volume Deflagration)



FEATURES:

- Self-sustained operation
  - No spark plugs
- Only one moving part
- Relatively low unsteadiness amplitudes
  - Lower thermal and mechanical stresses
  - Effluent easier to smooth
  - Fewer potential issues for downstream turbomachinery

- Readily operates with liquid fuels (gasoline, ethylene, kerosene)
- Effective lean operation (low T_{t4}'s) with bypass ejectors
- Unequivocally a pressure gain device
  - Only known PGC system to operate under static conditions

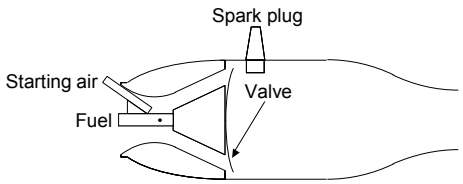
DRAWBACK

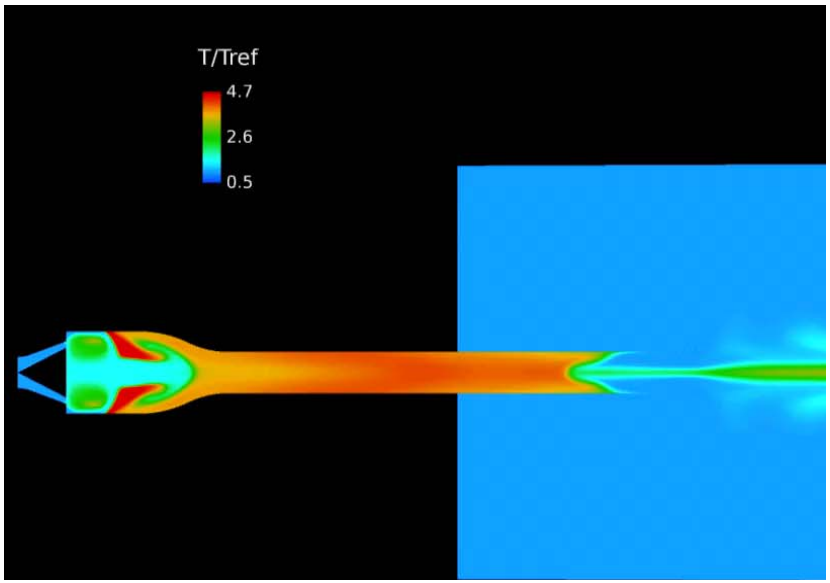
- Only Modest Pressure Gain is Possible
  - Confined (not constant) volume combustion

Practically: Features May Outweigh Drawback – Even Compared to Other PGC Approaches

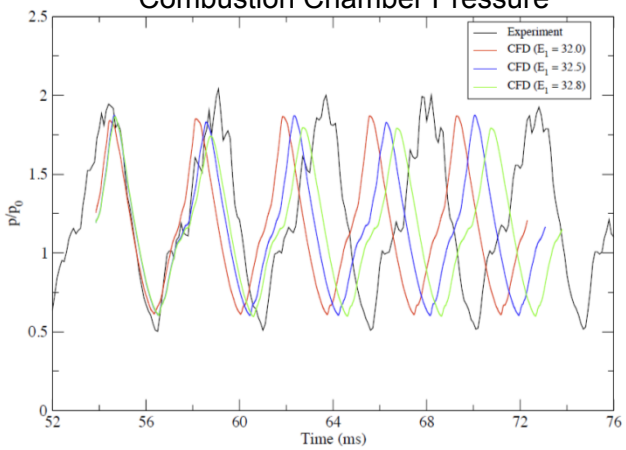
Motivation

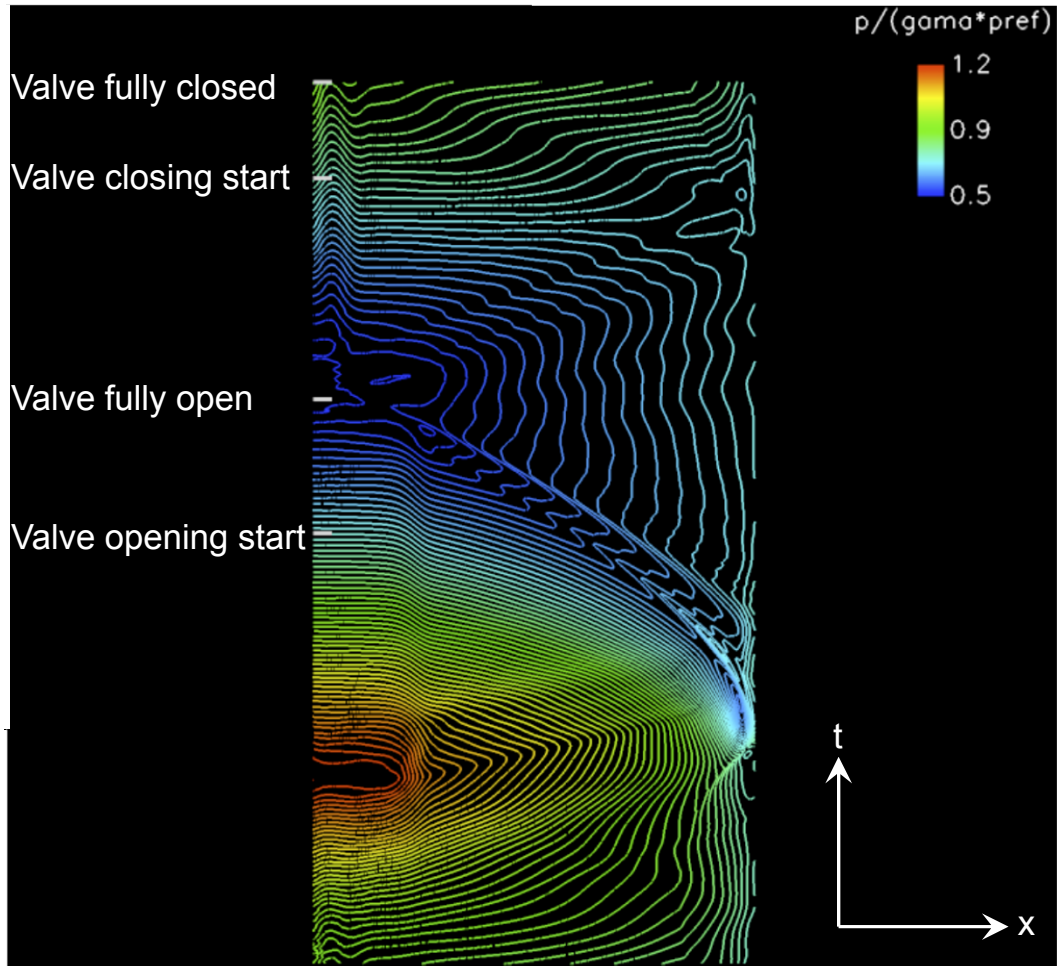
Resonant Pulse Combustion Basic Cycle





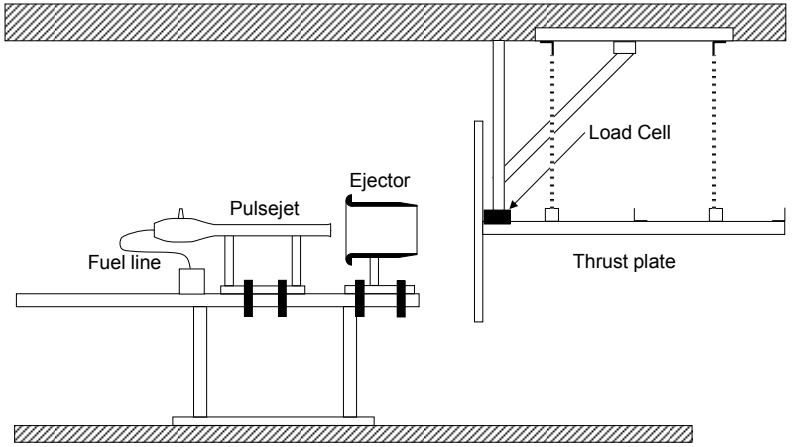
Combustion Chamber Pressure



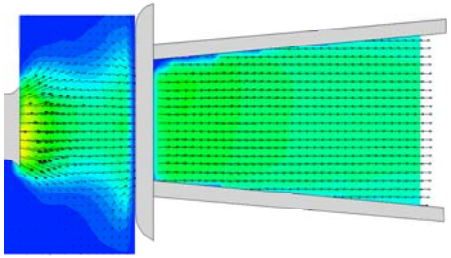


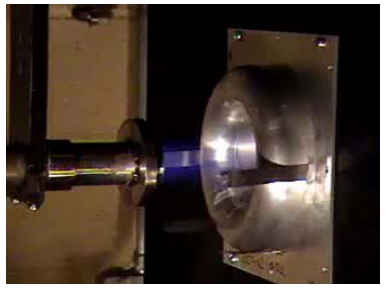
Experimental Investigations

Ejector Mixing and Pumping Optimization



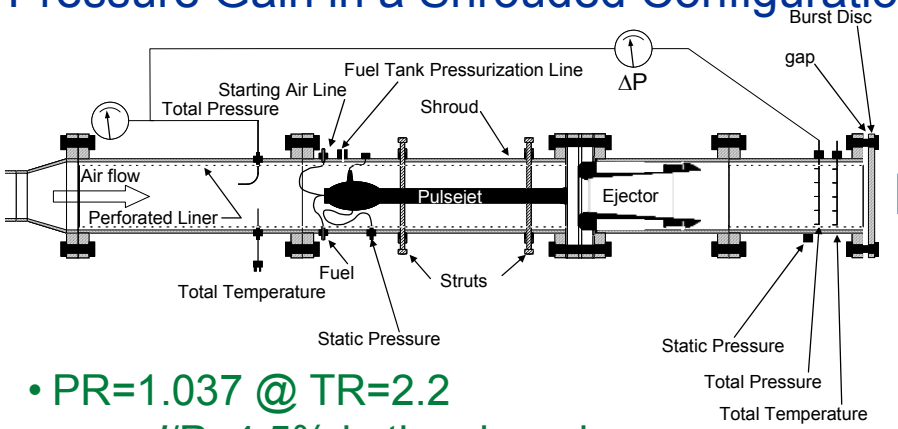
PIV Measured Flowfield





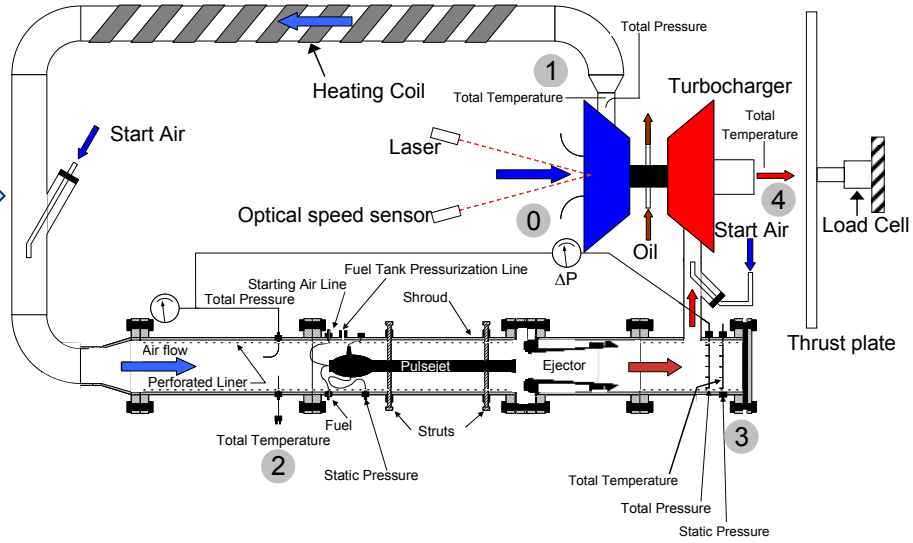
- 18:1 and greater entrainment ratios
- Thrust augmentation ratios up to 2.0
- Velocity fluctuations reduced by 83%

Pressure Gain in a Shrouded Configuration



- PR=1.037 @ TR=2.2
- rms p′/P=4.5% in the shroud
- Successful operation at 2 Atm. inlet pressure

Closed Loop Operation in a Gas Turbine

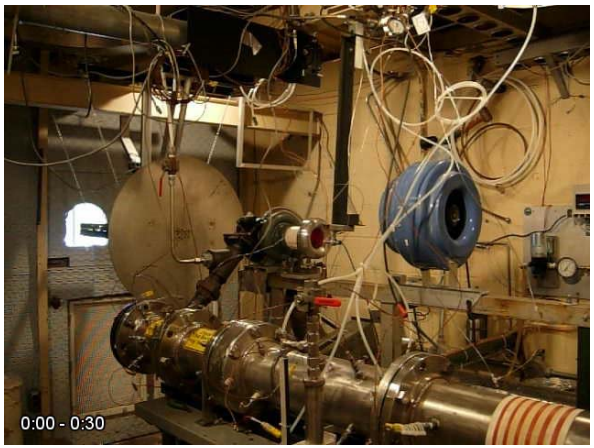


All Work Done With COTS Hobby Scale Pulse Combustor (Pulsejet)

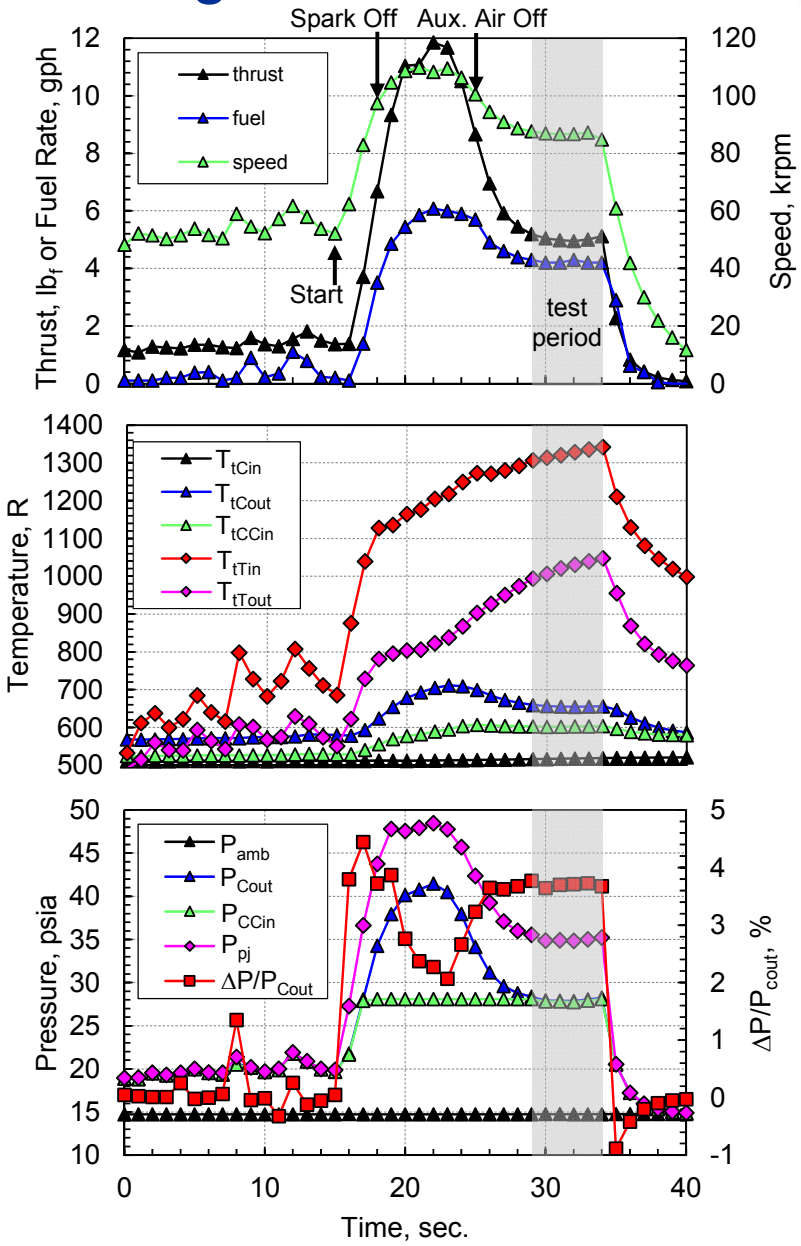
Experimental Investigations

Results:

- True closed loop operation @ SLS
  - All air supplied by compressor
- $(P_{Tin}/P_{cout} - 1)=3.5\%$ @ $T_{Tin}/T_{Cout}=2.2$
- Sustained operation on liquid fuel
  - Limited only by COTS reed valve
- Successfully produced thrust
- Demonstrated Benefit
  - Turbine slows and stops with conventional combustor at same T_{Tin}/T_{Cout}
- -20 dB noise reduction across Turbine
- 4% rms p'/P_{Cout} at turbine inlet



Without Qualification…It Works!

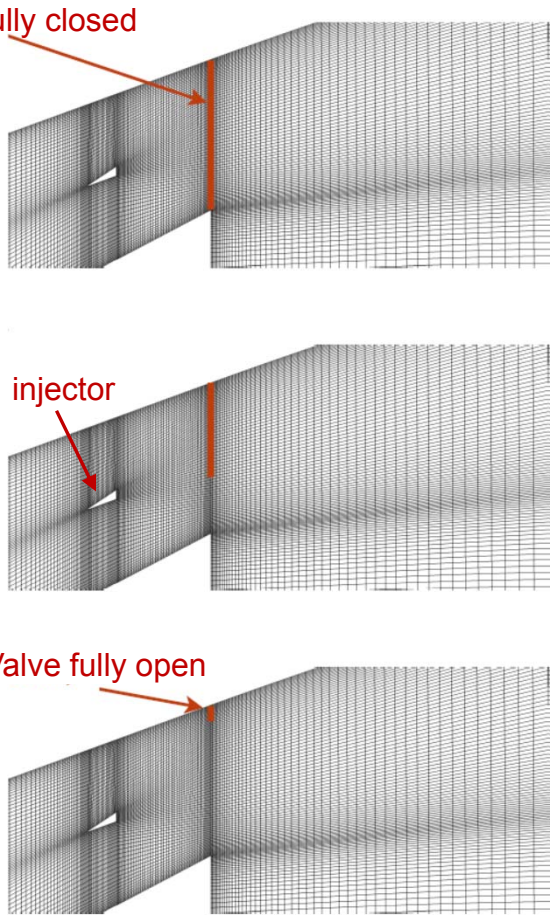


Numerical Investigations

What Happens to RPC at Representative P_3, T_3?

Approach:

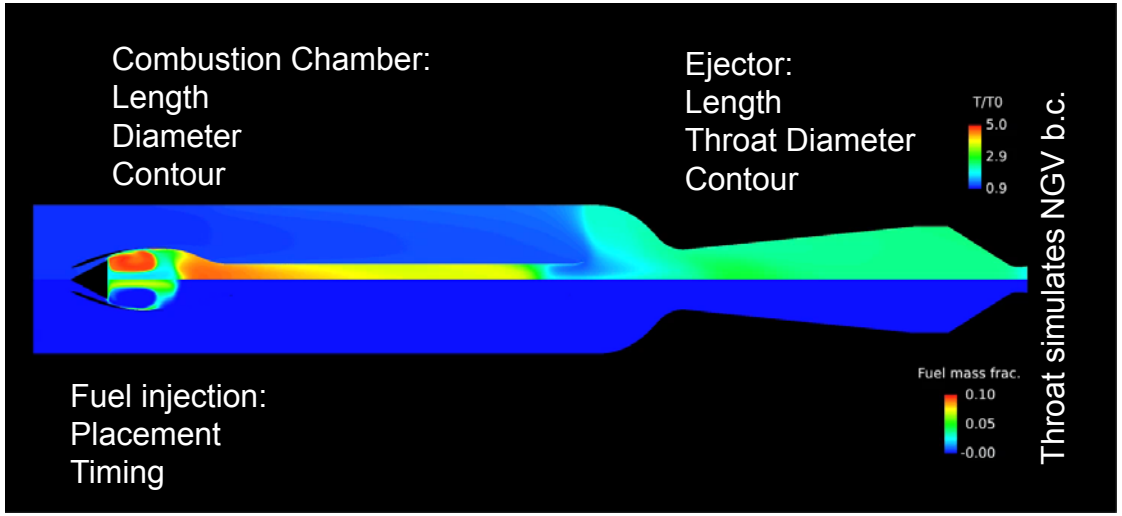
- Use in-house 2D axisymmetric CFD code
  - Turbulent
  - Contains detailed chemical kinetics
  - Adiabatic
  - Gaseous Jet-A fueled
  - Successfully applied to PDE, RDE, and SCRAM combustion
  - Pressure actuated, prescribed motion slide valve simulates reed
- Validate on atmospheric tests of experimental RPC
  - Compare thrust, mass flow rate, pressure traces, frequency
- Run at 10 Atm., 990 R inlet conditions
- Optimize for maximum pressure gain at $T_{t4}/T_{t3} \approx 2.0$
  - Fuel injector location
  - Inlet geometry
  - Combustion chamber size
  - Combustor length
  - Ejector/mixer parameters (length, position, diameter)
- Monitor emissions
  - Seek lowest index with largest pressure gain
- Seek minimum size



CFD as Predictive Design Tool

Numerical Investigations

Results To Date



- Emission Index < 10 g_{NOX}/kg_{fuel}
  - Lower pressure gain configurations showed values below 1.0!
- $(P_{t4}/P_{t3} - 1)$=3.3% @ T_{t4}/T_{t3}=2.4
  - A large improvement considering T_{t3}=990 R
- Relatively benign station 4 conditions
  - 7% rms p'/P_{t4}
  - 23% rms u'/u_4
  - 1.7% rms T'/T_{t4}

Inflow Vortex Motion is Key

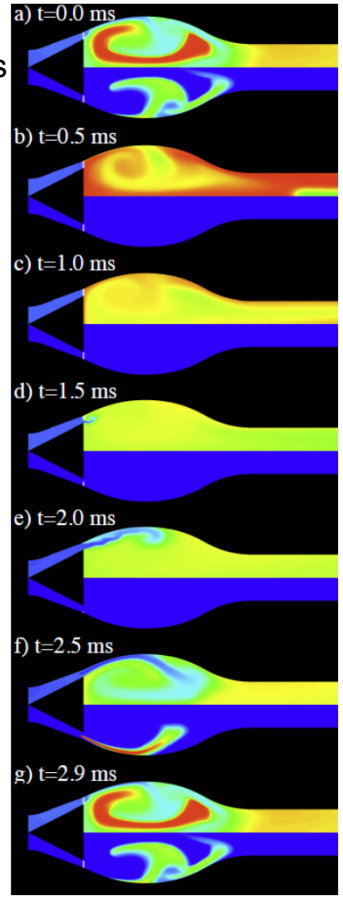
Temperature contours (top half) and fuel mass fraction contours (bottom half) at various times during one cycle (ϕ = 0.72).

Self-ignition via residual hot gas

Rapid confined combustion

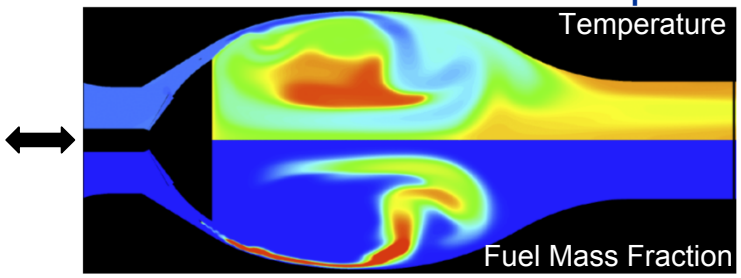
Expansion/acceleration

refill

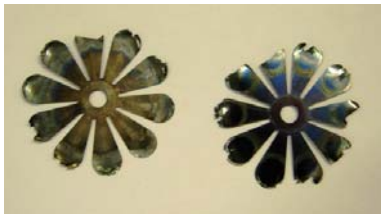


Ongoing and Future Directions

Alternative Valve Concepts

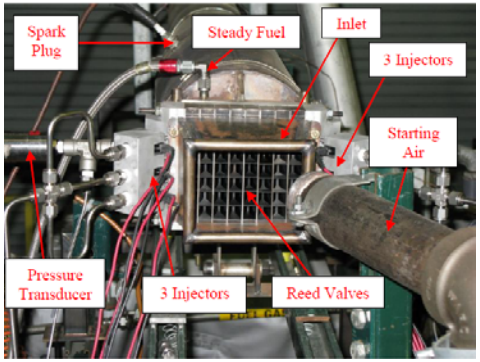


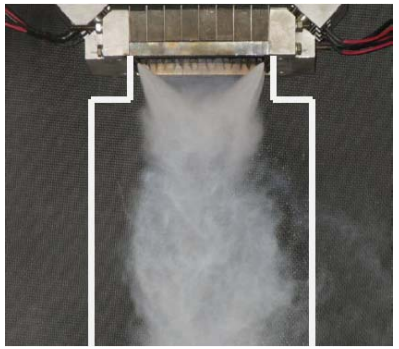
Life Extending Techniques for Existing Reed Valves



- Minimum length and diameter configuration
  - Computational
- Turbine interaction studies
  - Computational
- Active air valves
  - Still in planning stages
- High P_3, T_3 testing facilities
  - Still in planning stages

Active Fuel Modulation





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Concluding Remarks

Resonant Pulse Combustion (RPC):

- Represents a promising approach for achieving practical Pressure Gain Combustion (PGC)
- Has features which are well suited for gas turbine applications
  - Relatively low unsteadiness
  - Demonstrated approaches to achieving requisite overall lean operation
  - Few moving parts
  - Relatively low thermal and mechanical stresses
  - Self-sustaining
  - Low emissions potential
- Is a remarkably well developed concept
  - Liquid fueled operation
  - Demonstrated pressure gain
  - Demonstrated benefit to gas turbines
- Has potential for high P_3, T_3 operation
- Presents multiple opportunities for improvement and optimization that are achievable with current technology

RPC Could Be the Gateway to Making PGC Mainstream

END